Kinematic Improvement Differs Between Transradial Versus Partial-Hand Prosthesis Use Following Interlimb Training

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Kinematic Improvement Differs Between Transradial Versus Partial-Hand Prosthesis Use Following Interlimb Training

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To the students and faculty of the Georgia Institute of Technology

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ABSTRACT

About 33% of upper extremity amputees reject their prosthetic device due to perceived lack of functionality in daily life (Cusack et al., 2014). A way to bypass the lack of device use during the healing period is to begin training with a prosthesis simulator on the sound limb. This technique is known as interlimb transfer (ILT) and has the goal of allowing for the transfer of learned skills from the trained (non-amputated) limb to the affected limb. To investigate ILT, participants used one of two prosthesis simulators. The transradial prosthesis simulator (TrPS) simulated an amputation between the elbow and wrist, and the partial-hand prosthesis simulator (PhPS) simulated the loss of digits 1-3 at the metacarpophalangeal joint. In addition to being grouped by device (PhPS or TrPS), participants were also grouped into either the training or control group. Both groups underwent an identical pre-test and post-test on day 1 and day 5 of the study consisting of four motor tasks. The training group completed three days of the training paradigm on days 2-4 of the study. It was hypothesized that participants using a partial-hand prosthesis will have shorter movement duration, higher accuracy, higher peak velocity, and lower movement variability compared to participants using a transradial prosthesis. Additionally, it was hypothesized that participants partaking in interlimb training will show decreases in movement duration, increases in accuracy, increases in peak velocity, and decreases in movement variability compared to controls. By examining percent change from the first day of training (day 2) to the final day of training (day 4), it was found that more trials were completed, the time required to complete each trial decreased, and the number of errors committed decreased as the training paradigm progressed which indicates that an improvement was seen in all aspects of training. The PhPS group showed greater changes in

performance for all 3 measures compared to the TrPS group which supports the initial hypothesis. In regards to accuracy, for the TrPS group in the metal disk translation task, an ANOVA conducted on average number of errors for both groups (training and control) over the course of the experimental paradigm (day 1 and day 5) resulted in a near significant p-value of 0.0887 between groups (training vs. control). This suggests a trend towards support of the hypothesis with participants partaking in interlimb training showing increases in accuracy compared to controls. According to the preliminary analysis that has been conducted, interlimb transfer appears to improve functional performance when using a prosthesis simulator, and the PhPS group seems to improve the most.

INTRODUCTION

About 33% of upper extremity amputees reject their prosthetic device due to perceived lack of functionality in daily life (Cusack et al., 2014). Studies conducted by Cusack et al. (2014) examined the effects of bilateral transfer and suggested that beginning prosthetic training as soon as possible after amputation may serve as a means to enhance acceptance of the device and improve the probability that the prosthetic device will be used skillfully in daily life. It is common practice that prosthetic limb training does not begin until the affected limb is healthy enough to be fit with a prosthetic device, which is typically 3-6 months following an amputation (Webster et al., 2012; Malone, 1984). A way to bypass the lack of device use during the healing period is to begin training with a prosthesis simulator on the sound limb. This technique is known as interlimb transfer (ILT) and has the goal of allowing for the transfer of learned skills from the trained (non-amputated) limb to the affected limb.

Additionally, level of amputation has been found to affect device acceptance (Vogel et al., 2014). The two most common levels of upper limb amputation are transradial and partial-hand. The majority of these are distal to the wrist (partial-hand) and comprise 92% of upper-limb amputations, while transradial amputations are the most common major upper-limb amputation (Dillingham et al., 2002).

The purpose of my research is to examine the behavioral and kinematic effects of interlimb transfer with prosthesis simulator training (partial-hand or transradial) in participants performing skilled motor tasks. We hypothesize that participants using a partial-hand prosthesis will have shorter movement duration, higher accuracy, higher peak velocity, and lower movement variability compared to participants using a transradial prosthesis. Additionally, it was hypothesized that participants partaking in interlimb training will show decreases in movement duration, increases in accuracy, increases in peak velocity, and decreases in movement variability compared to controls.

LITERATURE REVIEW

Following an amputation, there is a healing period that must occur before an amputee can be fit with a prosthetic device. After this period, it has been found that about 33% of upper extremity amputees reject their prosthetic device due to lack of functionality in their daily life (Cusack et al., 2014). It is traditional practice to not begin rehabilitation training with a prosthesis until after wound healing is completed and the device has been fitted. However, it has been found that if training begins immediately following an amputation, it will fall within a window of opportunity for enhanced motor learning and device acceptance (Malone, 1984). Due to the fact that there is a period of healing that must occur prior to prosthesis fitting, other solutions, such as interlimb transfer, have been investigated in order to begin the training processes during the healing window.

Bilateral transfer is the transfer of learning to one side of the body as a result of training on the other side of the body. Investigations into bilateral transfer and its effectiveness have been conducted in an attempt to aid in an increased rate of prosthetic device acceptance. The majority of studies, such as the work by Weeks et al. (2003) and Yoo (2015), examine the bilateral transfer effects on movement with the use of an upper-limb prosthesis simulator beginning on a participant's dominant or non-dominant arm, then later switching to the other limb. One variable that has been manipulated to further investigate this is the order of limb training with one group training with the preferred limb then transferring to non-preferred and one training with non-preferred then transferring to preferred. Motor tasks used for the pre-test and post-test as well as for training on the opposite limb included the toggle-switch task, fine-aiming task, and prehension task. It was found that more difficult tasks resulted in a greater and more successful transfer (shorter movement time, shorter initiation time, and fewer errors) from the preferred to non-preferred limb and the opposite trend for an easier task (Weeks, Wallace, & Anderson, 2003). Overall time to complete each task from pre-test to post-test was compared as a measure of bilateral transfer.

Additionally, research has been conducted that investigates the extent of adaptability in the neural circuit and if this adaptation can be generalized to be transferred between limbs. While participants performed movement tasks using their arm and a manipulandum, a force field was applied and the change in movement and trajectory of the arm was recorded. Electroencephalography (EEG), non-invasive technique to record the brain's electrical activity, was used to examine the neural circuits. It was found that the addition and subsequent removal of the force field resulted in an aftereffect. The presence of this aftereffect and the altered trajectory of the arm raised questions as to if it was a neural network change responsible for this effect. An asymmetrical as opposed to a generalized transfer between limbs was found as only a difference was seen between dominant to non-dominant transfer (Criscimagna-Hemminger, Dochin, Gazzaniga & Shadmehr). The outcomes of this research indicate relevance of using techniques such as EEG to trace neural activity pattern changes before and after completion of a training paradigm.

My research aims to directly address the high rejection rates of prostheses by making use of the amputation healing period for motor training with a prosthesis simulator on the intact limb to improve motor leaning and performance.

METHODS

Participant Recruitment

Healthy, right-handed participants (N=33, mean age: 22.6 ±3.2 years) with no history of neurological deficits were recruited. Potential risks as a result of participating in the study were presented and consent forms were signed by all participants. The Edinburgh Handedness Inventory (Oldfield, 1971) was completed by each participant to ensure right hand dominance.

Prosthesis Simulators

In order to account for the two most common levels of upper limb amputation, two different prosthesis simulators are used (Figure 1). The transradial prosthesis simulator (TrPS) is used to simulate an amputation between the elbow and wrist. The TrPS is body-powered via a figure-of-nine harness that allows for voluntary control of opening the split-hook end-effector through glenohumeral flexion and scapular abduction. The partial-hand prosthesis simulator (PhPS) is used to simulate the loss of digits 1-3 at the metacarpophalangeal joint. The PhPS opens and closes via wrist extension and flexion while the thumb is constrained at a right angle secured along the palm, and the fore and middle fingers are strapped to a roof plate proximal to the distal joint of each finger. Each participant underwent the study using either the transradial (n=17) or partial-hand (n=16) prosthesis simulator.

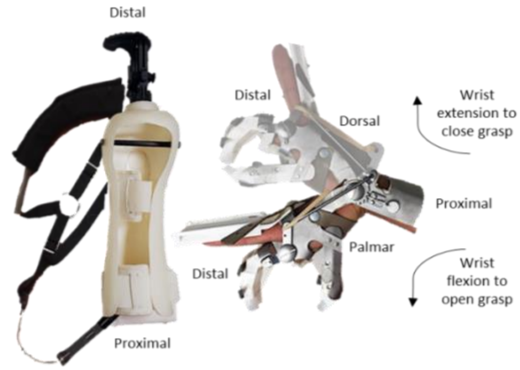

Figure 1. Left: Transradial prosthesis simulator (TrPS). Right: Partial-hand prosthesis simulator (PhPS).

Participant Preparation

Electroencephalography (EEG) is used on day 1 (pre-test) and day 5 (post-test) of the study as a non-invasive technique to record the brain's electrical activity. To prepare the participant for EEG, the ear lobes, forehead, and skin lateral to and below the left eye are cleaned with alcohol wipes. To aid in proper placement of the EEG cap, the participant's head is measured from nasion to inion. At ten percent of this distance, the most anterior electrodes are placed to ensure a secure and consistent fitting of the cap. Following the placement of the cap on the participant's head using the anterior electrodes as a guide, a chin strap is placed to secure the cap in place. After being filled with saline gel, one ear electrode is placed on each ear and two eye electrodes are placed- one lateral to and one inferior to the left eye. These electrodes serve as reference electrodes and aid in the removal of facial movement artifact, respectively. The electrodes are secured with tape and plugged into the coordinating wires on the cap. NuPrep exfoliating gel is used with wooden Q-tips on the opening of each electrode to remove the participant's hair from underneath the electrode, and a syringe is used to fill each electrode with saline gel to reduce electrical impedance and enhance signal fidelity (Atawala, 2019).

Neuroscan is used to ensure the impedance level for each electrode is at least 10kOhms. Confirmation that the EEG signals are responding properly is obtained by instructing the participant to blink three times, clench their jaw, and move their eyes right and left (Atawala, 2019).

A Motion Monitor software is used to collect motion data which will be used to determine effector peak velocity. Two sensors are placed on the prosthesis simulator- one on either side of the end-effector. The motion monitor sensor is then calibrated to the participant’s body placing the calibration sensor between C7 and T1, on the acromioclavicular joint, trigonum spinae, angulus inferior, angulus acromialis, coracoid process, ulna, radius, and on the fixed jaw of the prosthesis.

Experimental Paradigm

In addition to being grouped by device (PhPS or TrPS), participants were also grouped into either the training or control group. Both groups underwent an identical pre-test and post-test on day 1 and day 5 of the study. The training group completed three days of the training paradigm on days 2-4 of the study.

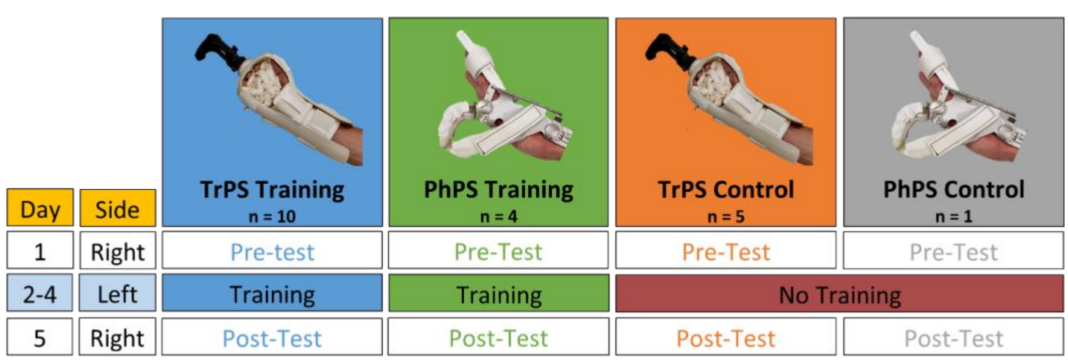

Figure 2. Participants undergo an initial testing session using their right (dominant) side, comprised of four motor tasks. Training groups undergo 3 days of training using their nondominant, left side, before returning to using their right for the test session on day 5. The control group only performed the initial testing session and the final test on day 5.

- **Testing Paradigm**

Figure 3. Participants undergo a pre-test (day 1) and post-test (day 5) comprised of four motor tasks using the prostheses on their right (dominant) side. The four testing tasks (from right to left) are- metal disk translation, markers, circle tracing, and ball toss.

The testing paradigm for day 1 (pre-test) and day 5 (post-test) were identical and consisted of four motor tasks accompanied by EEG and motion monitor recordings. Testing tasks were selected that mimicked those of the Action Research Arm Test (ARAT) which is commonly used as a measure of upper-limb function (Lyle, 1981). All testing tasks are completed with the TrPS or PhPS device worn on the dominant (right-side). Prior to each task, participants are given verbal instructions on how to complete each task along with the instruction to complete the tasks as quickly and accurately as possible. Following these instructions, a brief video was played to demonstrate how to perform the task. The timing of each testing task is driven by the home button. The home button is located on the table in front of the participant and serves to synchronize the rest period between each trial. Participants begin by pressing down the home button with the prosthesis (triggering a light to turn on) until the light turns off, which acts as a “Go” signal to begin the task. Following the completion of each movement, the participant returns to the home button until instructed by the light to begin the next movement.

The four testing tasks consist of metal disk translation, marker rotation, circle tracing, and ball toss (Figure 3). For the metal disk translation task, the participant is seated in front of a table containing five circuit boards labeled 1 (left-most) to 5 (right-most). Following the pressing of the home button, the participant is tasked with moving a metal disk from circuit 5 to 1, 5 to 2, 5 to 3, and 5 to 4 for 4 metal disks and a total of 20 trials. Errors are recorded according to how accurately each metal disk is placed in relation to the center of the circuit board.

For the markers task, the same circuit board and table set-up is used as in the metal disk translation task. A marker cradle, containing two horizontal grooves for each end of the marker, is placed over circuit 5 and a marker is placed horizontally in the cradle. The participant begins at the home button and reaches for the marker and transports it by the cap to place it vertically on circuit 1. The same process is repeated to transfer a second marker from the cradle to circuit 3 for a total of 20 trials. Errors are recorded according to how accurately each marker is placed in relation to the center of the circuit board.

For the circle tracing task, all circuits are removed from the table and a clipboard with 2 concentric circles is placed on the center of the table. The experimenter places a dry-erase marker in the split-hook of the prosthesis and the participant is instructed to begin by pressing the home button, trace the circle while attempting to remain within the boundaries of the concentric circles, and return to the home button. This process is repeated for 20 trials.

In the final testing task, ball toss, a Velcro dartboard is placed on the floor three feet in front of the participant. The participant begins at the home button, reaches for the Velcro ball, and throws the ball underhand at the dartboard aiming for a "bullseye." This process is repeated for 6 balls and a total of 10 trials (6 balls per trial). If the ball is dropped during the grasp or throw, it is counted as a miss. Balls that land on the dartboard are scored according to which concentric ring they land on- with a score of 1 awarded to a "bullseye" and a score of 3 awarded to placement on the outermost rim of the dartboard.

- **Training Paradigm**

Figure 4. Participants in the training group undergo three days of training (days 2-4) comprised of four motor tasks using the prostheses on their left (non-dominant) side. The four training tasks (from right to left) are- wooden disk translation, tubes and rods, key and lock, and operation.

The training group underwent three days of training (days 2-4) by completing a series of four motor tasks with the prosthesis simulator on their non-dominant side. The four training tasks mimic kinematic aspects of the testing tasks. Prior to each task, participants are given verbal instructions on how to complete each tasks as long with the instruction to complete as many repetitions as they can within 8 minutes. The participant begins at and returns to the home button between each trial. The home button light does not turn on/off to indicate when to begin the next trial as all four training tasks are self-paced. The same four training tasks are used for all three days of training.

The four training tasks are wooden disk translation, tubes and rods, key and lock, and operation (Figure 4). The wooden disk translation task is similar to the metal disk translation task from the testing paradigm with the exception that the disks are made of lighter wood. For the wooden disk translation, the participant is seated in front of a table containing five circuit boards labeled 1 (left-most) to 5 (right-most). Following the pressing of the home button, the participant is tasked with moving a wooden disk from circuit 1 to 5, 1 to 4, 1 to 3, and 1 to 2 for 4 wooden disks. This process is self-paced and wooden disks are transported for a total of 8 minutes. Errors are recorded according to how accurately each disk is placed in relation to the center of the circuit board.

For the tubes and rods task, the circuit boards are removed from the table and are replaced with two rod boards. Each rod board consists of two rods- one large and one small. Two tubes (one large and one small) are placed on the corresponding rods on the left-most rod board. After beginning at the home button, the participant is instructed to pick up a tube from the left rod board, transport the rod, and place it in a controlled manner onto the rod of corresponding size on the right-most rod board. This process is repeated for the remaining tube on the left rod board. The transport of both tubes is repeated from the right rod board to the left rod board for a total of 8 minutes.

In the key and lock task, a lock is secured onto the vertical wall of the table. A key is placed in the lock and turned 90° to the right. After starting at the home button, the participant reaches to grab the key, turns it 90° to the left ("unlocking it"), and removes the key from the lock before returning back to the home button. Next, the participant inserts the key back into the lock and turns it 90° to the right ("locking it") before returning to the home button. This sequence is repeated for 8 minutes.

For the final training task, operation, an apparatus with two holes is placed on the table in front of the participant. A tube is placed in one of the holes, and the participant is instructed to remove the tube from the hole without touching the tube to the sides of the hole. Once the tube is removed from the hole, the participant places the tube in the other hole in the apparatus without touching the tube to the sides of the hole. This pattern is repeated for 8 minutes.

Kinematic Data Processing

The kinematic data is the area of interest for the initial phases of this study. As the study progresses and the data from more participants are collected, the EEG data will be incorporated into the analysis. Peak effector velocity is found via MATLAB using the data from the motion monitor and each movement is separated into phases (i.e., reach, transport, return). Coefficient of variation (CV) is used to quantify movement variability for movement duration and peak velocity. Additionally, number of errors per task, duration per movement, and duration per task are analyzed for testing days. Number of trials completed, number of errors per task, and duration per task are analyzed for training tasks and will be used to compute percent change from the first to last day of training to determine the effect training had on motor learning. These kinematic measures will be compared between training and control groups as well as between TrPS and PhPS groups to determine how training and the level of amputation affects motor learning, respectively.

RESULTS

Effects of Training

The effects of training were evaluated as the percent change in performance from the first day of training (day 2) to the final day of training (day 4). Performance on all four training tasks (wooden disk translation, tubes and rods, key and lock, and operation) was averaged and parameters reported included number of trials completed, duration per trial, and number of errors per trial. A positive increase in the percent change of trials completed was found and indicates that more trials were completed as the training paradigm progressed. A negative percent change for trial duration and number of errors per trial was found which indicates that the time required to complete each trial decreased and the number of errors committed decreased as the training paradigm progressed (Figure 5).

Figure 5: Percent change as a result of training. The percent change from Day 2 (first day of training) to Day 4 (final day of training) are shown in terms of number of trials completed, duration of each trial, and number of errors per trial. All parameters are shown as an average across all four training and are divided by device (TrPS or PhPS). Bars show standard error.

Coefficient of Variation

Coefficient of Variation is calculated by dividing the standard deviation by the mean with a more negative coefficient of variation being favorable as it indicates less variability. Coefficient of Variation values were calculated on the duration of each trial for the metal disk translation and ball toss tasks for the TrPS group for both the pre-test and post-test. Coefficient of Variation values are plotted relative to the first movement of the pre-test and were calculated as the difference from pre-test movement 1. For the metal disk translation task, both control and training groups had a more negative coefficient of variation in the post-test as compared to the pre-test (Figure 6). In the ball toss task, there was not much change in the coefficient of variation for the control group from pre-test to post-test as both sets of coefficient of variation values were positive. For the training group, the post-test duration values had a more negative coefficient of variation as compared to the pre-test (Figure 7).

Coefficient of Variation was also calculated on the peak velocity of each phase of movement during the metal disk translation task. Coefficient of Variation of Peak Velocity values are plotted relative to the first trial with each trial being the average of four movements (Figure 8).

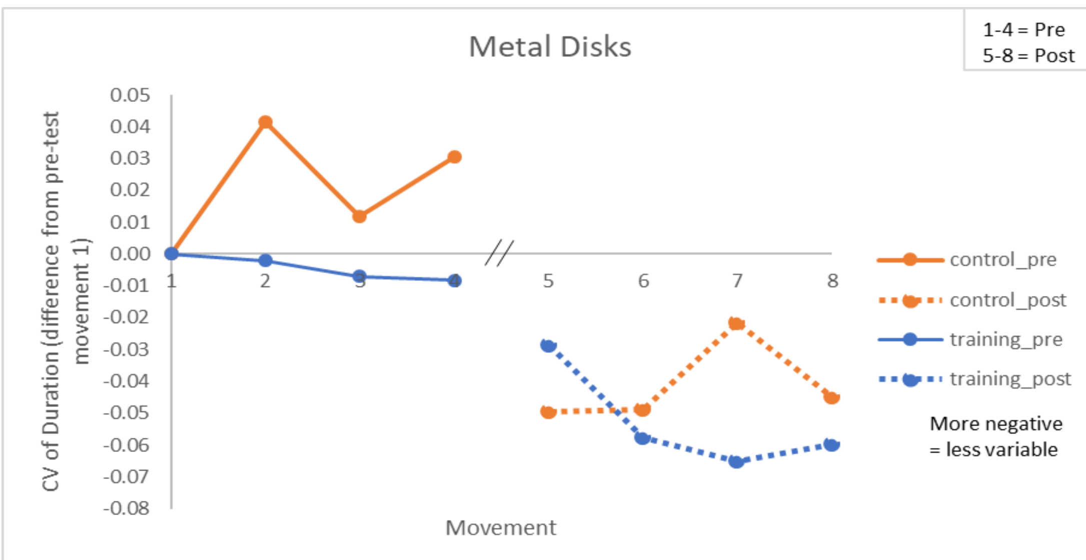

Figure 6. Coefficient of Variation of Duration for Metal Disk Translation Task. Coefficient of Variation values are shown for the TrPS group for both pre-test and post-test. A more negative Coefficient of Variation indicates less variability.

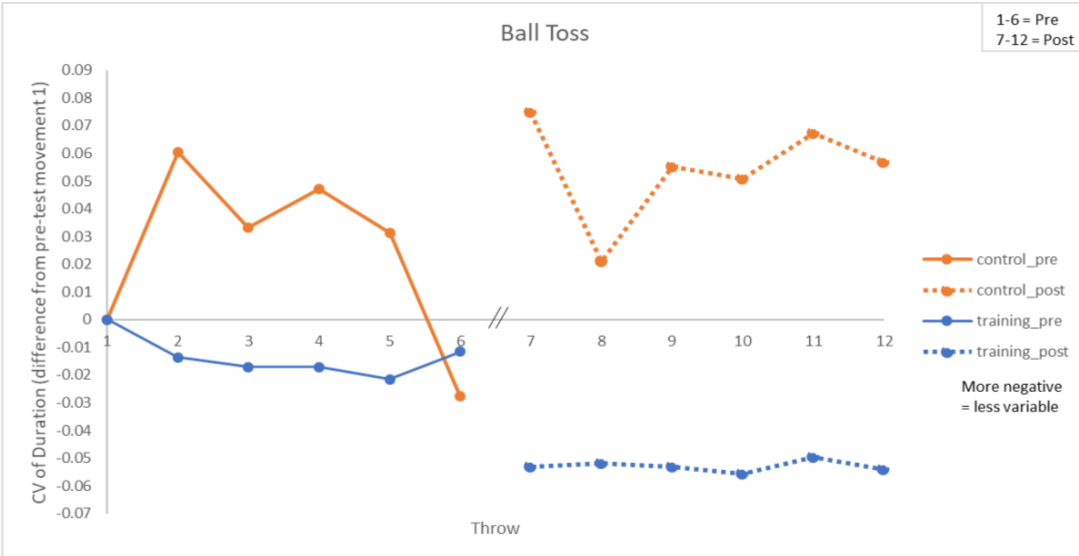

Figure 7. Coefficient of Variation of Duration for Ball Toss. Coefficient of Variation values are shown for the TrPS group for both pre-test and post-test. A more negative coefficient of variation indicates less variability.

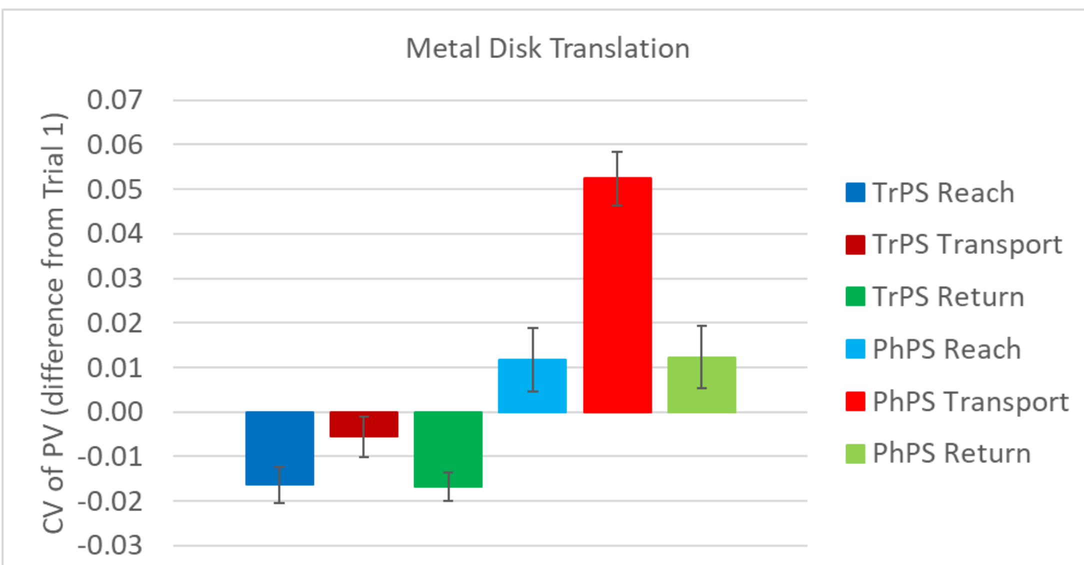

Figure 8. Coefficient of Variation (CV) of Peak Velocity (PV) for metal disk translation task. CV of PV is broken down per movement phase and is shown for both TrPS and PhPS groups. Bars show standard error.

Training versus Control, Day 1 compared to Day 5

Focusing on the metal disk translation and ball toss tasks, various parameters such as average duration and number of errors/misses are reported for both the pre-test (day 1) and post-test (day 5). ANOVAs were run for each parameter and p-values that indicate overall significance, significance between groups (training vs. control), or significance between days (day 1 vs. day 5) are reported.

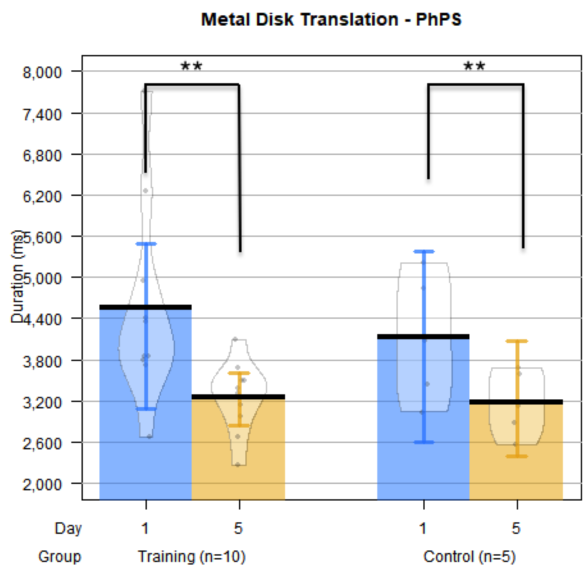

Figure 9. Average duration across all movements for metal disk translation task. Day 1 (pre-test) and Day 5 (post-test) data is shown for both the training and control PhPS groups. A p-value of 0.00493 was obtained between day 1 and day 5.

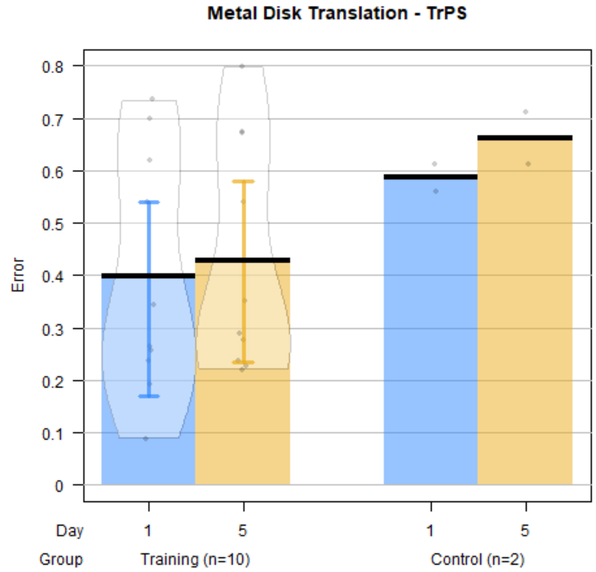

Figure 10. Average number of errors per movement for the metal disk translation task. Errors are recorded according to how accurately each metal disk is placed in relation to the center of the circuit board. Day 1 (pre-test) and Day 5 (post-test) data is shown for both the training and control TrPS groups. A p-value of 0.0887 was obtained between groups (training vs. control).

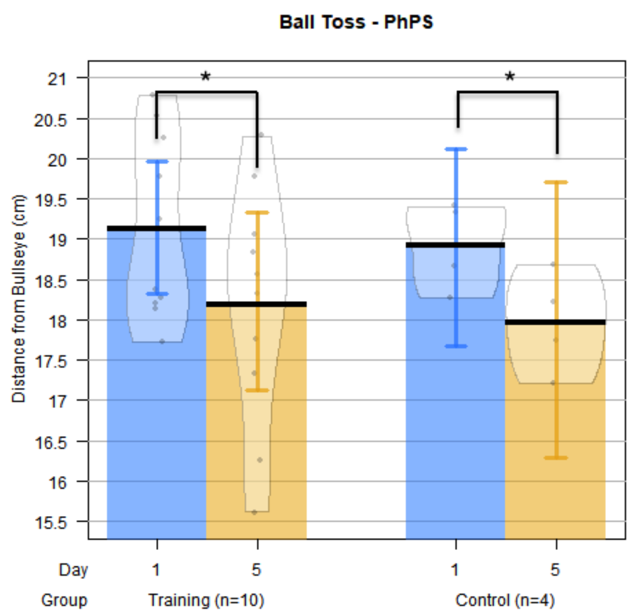

Figure 11. Average distance of the ball from bullseye for the ball toss task. Day 1 (pre-test) and Day 5 (post-test) data is shown for both the training and control PhPS groups. A p-value of 0.0428 was obtained between days (Day 1 vs. Day 5).

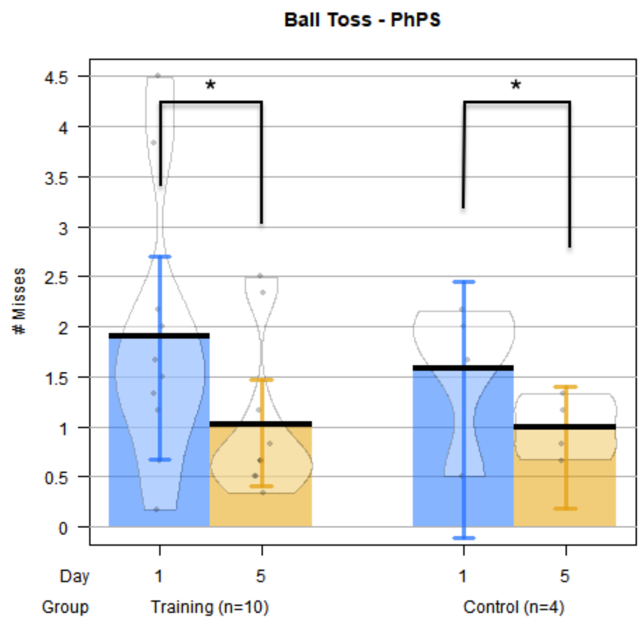

Figure 12. Average number of misses per trial for ball toss task. Each trial consisted of 6 balls. Day 1 (pre-test) and Day 5 (post-test) data is shown for both the training and control PhPS groups. A p-value of 0.0434 was obtained between days (Day 1 vs. Day 5).

CONCLUSION

The purpose of this study was to examine the behavioral and kinematic effects of interlimb transfer with prosthesis simulator (partial-hand and transradial) training in participants performing skilled motor tasks. It was hypothesized that participants using a partial-hand prosthesis will have shorter movement duration, higher accuracy, higher peak velocity, and lower movement variability compared to participants using a transradial prosthesis. By examining percent change from the first day of training (day 2) to the final day of training (day 4), it was found that more trials were completed, the time required to complete each trial decreased, and the number of errors committed decreased as the training paradigm progressed (Figure 5). This indicates that an improvement was seen in all aspects of training. The PhPS group showed greater changes in performance for all 3 measures compared to the TrPS group which supports the initial hypothesis.

It was also hypothesized that participants partaking in interlimb training will show decreases in movement duration, increases in accuracy, increases in peak velocity, and decreases in movement variability compared to controls (no training). In order to examine movement variability, coefficient of variation was calculated for the duration of each trial for the metal disk translation and ball toss tasks with a more negative coefficient of variation indicating less variability. Metal disk translation and ball toss were selected to be compared as they represent the easiest and most difficult testing tasks, respectively. For the metal disk translation task, both control and training groups had a more negative coefficient of variation in the post-test as compared to the pre-test (Figure 6). In the ball toss task, there was not much change in the coefficient of variation for the control group from pre-test to post-test. For the training group, the post-test duration values had a more negative coefficient of variation as compared to the pre-test (Figure 7). This suggests that a ceiling effect may be present for less complex tasks (metal disk translation), but with increased task complexity, divergence is seen between training and control groups in kinematics. In regards to accuracy, for the TrPS group in the metal disk translation task, an ANOVA conducted on average number of errors for both groups (training and control) over the course of the experimental paradigm (day 1 and day 5) resulted in a near significant p-value of 0.0887 between groups (training vs. control). Although this value is not significant at an alpha value of 0.05, it suggests a trend towards support of the hypothesis with participants partaking in interlimb training showing increases in accuracy compared to controls.

According to the preliminary analysis that has been conducted, interlimb transfer appears to improve functional performance when using a prosthesis simulator, and the PhPS group seems to improve the most. This is demonstrated both in the training, where partial-hand participants showed much higher rates of improvement, and in the testing sessions, through kinematic stability, velocity, and a greater speed-accuracy tradeoff compared to transradial prosthesis simulation.

FUTURE DIRECTIONS

The next step of data analysis includes analyzing the EEG beta band activity in terms of power. A decrease in power in a region of the brain indicates higher levels of activity (Makeig, 1993). Power levels will be compared between training and control groups of both amputation levels (PhPS and TrPS) using scalp maps. Power analysis has the potential to indicate differences in activation levels of different brain regions and shifts in contralateral versus ipsilateral activation patterns. If differences are found, it would provide evidence for differential activation between prosthesis device groups, potentially supporting a mechanism that may be differentially controlled at differing levels of amputation.

Future work will also examine how neuromodulation such as transcranial direct current stimulation may be able to enhance the effects of interlimb transfer. Transcranial magnetic stimulation (TMS) is a common method for examining interhemispheric interactions within the sensorimotor system (Noh et al., 2012). Additionally, this work has been conducted on sound-limb prosthesis users. It is predicted that these results will translate to amputees as there is no central neurological injury in amputation, but there is always increased validity in using the actual injury population for research.

REFERENCES

Atawala, N. (2019). Neurobehavioral Patterns during Action Observation and Execution of Complex Goal-Directed Movements. SMARTech.

Criscimagna-Hemminger, S. E., Donchin O, Gazzaniga, M. S., & Shadmehr, R. Learned dynamics of reaching movements generalize from dominant to nondominant arm. (0022-3077 (Print)).

Cusack, W. F., Patterson, R., Thach, S., Kistenberg, R. S., & Wheaton, L. A. (2014). Motor performance benefits of matched limb imitation in prosthesis users. *Experimental Brain Research, 232*(7), 2143-2154. doi:10.1007/s00221-014-3904-2

Dillingham TR, Pezzin LE, MacKenzie EJ. (2002). Limb amputation and limb deficiency: Epidemiology and recent trends in the United States. South Med J, 95: 875-883.

Lyle, RC. (1981). A performance test for assessment of upper limb function in physical rehabilitation treatment and research. Int J Rehabil Res, 4(4): 483-492.

Makeig S. (1993). Auditory Event-Related Dynamics of the EEG Spectrum and Effects of Exposure to Tones. Electroencephalography and Clinical Neurophysiology, 86: 283-293.

Malone, J.M., Fleming, L. L., Roberson, J., Whitesides, T. E., Leal, J. M., Poole, J. U., & Grodin, R. S. Immediate, early, and late postsurgical management of upper-limb amputation. (0748-7711 (Print)).

Noh, N. A., Fuggetta, G., Manganotti, P., & Fiaschi, A. (2012). Long lasting modulation of cortical oscillations after continuous theta burst transcranial magnetic stimulation. PloS one, 7(4), e35080. https://doi.org/10.1371/journal.pone.0035080

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia, 9(1), 97–113.

van Wijk, B., Beek, P., & Daffertshofer, A. (2012). Neural synchrony within the motor system: what have we learned so far? *Frontiers in Human Neuroscience, 6*, 252.

Velasques, B., Ferreira, C., Teixeira, S. S., Furtado, V., Mendes, E., Basile, L., Cagy, M., Ribeiro, P. Motor learning processes: an electrophysiologic perspective. (0004-282X (Print)).

Vogel TR, Petroski GF, Kruse RL. (2014). Impact of amputation level and comorbidities on functional status of nursing home residents after lower extremity amputation. J Vasc Surg, 59(5): 1323-1330.

Webster JB, Hakimi KN, Williams RM, Turner AP, Norvell DC, Czerniecki JM. (2012). Prosthetic fitting, use, and satisfaction following lower-limb amputation: A prospective study. JRRD, 49: 1493-1504.

Weeks, D. L., Wallace, Sa., & Anderson, D. I. (2003) Training with an upper-limb prosthetic simulator to enhance transfer of skill across limbs. (0003-9993 (Print)).

Yoo, I. (2015) Specialization in interlimb transfer between dominant and non-dominant hand skills. (0915-5287 (Print)).